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Predicting Frost Heaving Susceptibility of Arizona Soils

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In 1971 a study was initiated to determine the heaving susceptibility of six Arizona forest soils. A total of 15 variables were used in a stepwise regression analysis to develop an equation for predicting frost heaving susceptibility. By using the variables—bulk density, sand content, and calcium—an equation was constructed which accounted for 83 percent of the total variation (R^2) in heaving.

Keywords: Frost heaving, *Pinus ponderosa*.

INTRODUCTION

Frost heaving is a serious problem in the regeneration of many tree species. In northern Arizona it is a major cause of first-year mortality of ponderosa pine (*Pinus ponderosa* Laws.) seedlings (Larson 1961).

A review of the literature (Heidmann 1974b) revealed that frost heaving is due to a segregation of soil water, which freezes into layers of ice variously referred to as lenses, needle ice, stalactite ice, or comb ice (kameis) (Schramm 1958).

Soil water segregates primarily because water in the smaller soil pores and adsorbed on soil particles freezes at a lower temperature than pure water. The difference between the normal and depressed freezing points provides the free energy necessary to draw water to the freezing zone and to lift the soil (Martin 1958).

Water segregates in soils that are permeable to water flow and develop a negative pressure or tension. Both permeability and negative pressure are

related to soil pore size, which is a function of soil particle size or texture. A silty soil is ideally suited to frost heaving because the pores are large enough for good permeability but small enough for a negative pressure to develop (Penner 1958).

In 1971, a comprehensive study of frost heaving in Arizona was begun to identify frost-susceptible soils, and to find possible methods of controlling heaving. This Note is limited to a discussion of the former subject.

EXPERIMENTAL APPROACH

Since pore size is a function of particle size or texture, it was decided that a study of frost heaving should include soils of differing textures.

Measurements of various soil characteristics were used in regression analysis in an attempt to find an equation for predicting heaving. Parameters studied were those that appeared to be related to water availability and flow: particle size, bulk density, type and amount of clay minerals, cation exchange capacity, total calcium and magnesium, and exchangeable amounts of sodium, calcium, and magnesium. Factors such as thermal conductivity that do not appear to be strongly correlated with frost heaving (Probst 1965) were not studied.

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METHODS AND RESULTS

Collection of Soil Samples

Soils of varying texture from six locations within a 40-mile radius of Flagstaff, Arizona were selected for study (table 1). Selections were based on soil survey information (Williams and Anderson 1967). At each of the six locations, soil samples were collected from the 0 to 2.5, 2.5 to 7.6, and 7.6 to 15.2 cm depths.

Soil Tests

The bulk density of each soil was determined by the sand-cone method (Black 1965). The sand-cone method is especially useful when samples are collected from soils containing rocks and it is difficult to obtain undisturbed cores.

The bulk densities for the six soils and three depths ranged from less than 1 at S-3 West (S-3 W) to 1.79 at Beaverhead Flat (BF) (table 1). Soils with low bulk densities are usually characterized by higher percentages of the finer soil particles (clays and silts); soils with higher bulk densities are made up of coarser particles (sand and gravels).

Soil particle size was determined by the hydrometer method of Bouyoucos (Black 1965). Soil texture data are also given in table 1.

One of the soils studied, Tie Park (TP), had essentially no sand, while two, Kelly Tank and BF, were from one-half to two-thirds sand. All of the soils have a fairly high silt content.

Table 1.--Bulk density and textural classification[1] for six soils from northern Arizona at three depths

Location and soil depth (cm)	Elevation	Bulk density	Sand	Silt	Clay	Organic matter	Textural classification[1] (USDA system)	Heaving Characteristics
	Feet		- - - Percent - - -					
Tie Park (TP)	7,400							Unknown
0 - 2.5		1.21	0	66	34	4.33	Silty clay loam	
2.5 - 7.6		1.08	1	66	33	1.93	Silty clay loam	
7.6 - 15.2		1.27	0	62	38	1.90	Silty clay loam	
Beaverhead Flat (BF)	3,800							Unknown
0 - 2.5		1.56	60	30	10	.33	Sandy loam	
2.5 - 7.6		1.79	52	34	14	.20	Sandy loam	
7.6 - 15.2		1.75	51	32	17	.20	Loam	
Fort Valley Experimental Forest-- S-3 West (S-3W)	7,300							Excessive
0 - 2.5		.93	15	68	17	2.27	Silt loam	
2.5 - 7.6		.97	13	66	21	3.43	Silt loam	
7.6 - 15.2		1.07	9	66	25	1.87	Silt loam	
S-3 East (S-3E)	7,300							Little heaving
0 - 2.5		1.14	16	64	20	2.47	Silt loam	
2.5 - 7.6		1.09	15	67	18	1.47	Silt loam	
7.6 - 15.2		1.20	10	66	24	.77	Silt loam	
Beaver Creek Watershed 14 (W-14)	7,400							Unknown
0 - 2.5		1.04	10	61	29	5.20	Silty clay loam	
2.5 - 7.6		1.24	3	66	31	6.83	Silty clay loam	
7.6 - 15.2		1.32	5	66	29	2.57	Silty clay loam	
Kelly Tank (Kelly)	7,200							Moderate
0 - 2.5		1.08	63	24	13	2.57	Sandy loam	
2.5 - 7.6		1.34	61	26	13	3.73	Sandy loam	
7.6 - 15.2		1.50	57	28	15	3.20	Sandy loam	

[1]As determined by the hydrometer method.

The amount of organic matter varied from less than 1 percent at BF to 7 percent at Watershed 14 (W-14) (table 1).

A sample from each soil depth was sent to the Department of Soils, Water, and Engineering, the University of Arizona, for analysis of clay minerals and soil nutrients. The clay mineral analysis, done by X-ray diffraction, was used to determine the relative amounts of montmorillonite (Mt.), mica (Mi.), vermiculite (Vm.), and Kaolinite (Ka.). Each soil was also analyzed for total calcium (Ca) and magnesium (Mg) content; cation exchange capacity (CEC); and exchangeable calcium, sodium, and magnesium (ExCa, ExNa, ExMg).

The clay mineral type and relative content varied considerably (table 2). Montmorillonite content was highest in samples from BF and TP, which exhibited the greatest total heaving in laboratory freezing tests. None of the samples contained chlorite.

Soil nutrients and CEC also varied considerably (table 2).

Freezing Tests

Soil frost-heaving experiments were conducted in the laboratory using a specially constructed chest

Table 2.--Results of mineral analysis for six soils in northern Arizona[1]

Location and soil depth (cm)	Clay mineral type				Ca	Mg	CEC	ExCa	ExNa	ExMg
	Mt.	Ka	Vm	Mi						
					Meg		- - - - *Meg/100 g* - - - -			
Tie Park (TP)										
0 - 2.5	4	2	1	2	2.7	2.7	28.9	17.2	.18	11.5
2.5 - 7.6	4	2	2	2	1.4	1.1	32.4	21.0	.31	11.1
7.6 - 15.2	4	2	2	2	1.5	1.1	33.7	22.4	.33	11.0
Beaverhead Flat (BF)										
0 - 2.5	5	2	1	2	18.6	3.4	16.6	14.8	.02	1.8
2.5 - 7.6	5	1	1	2	7.6	1.9	23.5	20.1	.04	3.4
7.6 - 15.2	5	2	1	2	4.4	1.4	22.6	18.6	.06	4.0
Fort Valley Experimental Forest-- S-3 West (S-3W)										
0 - 2.5	1	3	1	3	4.3	2.8	33.8	23.5	.07	10.2
2.5 - 7.6	1	3	1	3	3.5	2.3	34.7	24.0	.07	10.6
7.6 - 15.2	1	3	1	3	3.5	2.2	35.9	25.2	.11	10.6
S-3 East (S-3E)										
0 - 2.5	1	2	1	3	4.9	3.1	36.6	22.9	.06	9.7
2.5 - 7.6	2	3	1	3	4.9	3.1	38.8	27.2	.07	11.5
7.6 - 15.2	2	2	1	3	4.2	3.7	32.5	20.4	.06	12.0
Beaver Creek Watershed 14 (W-14)										
0 - 2.5	4	2	1	2	5.8	5.2	45.4	28.3	.13	17.0
2.5 - 7.6	3	3	1	3	6.7	4.5	41.0	28.2	.14	12.7
7.6 - 15.2	3	3	1	3	6.8	5.2	43.3	28.5	.15	14.6
Kelly Tank (Kelly)										
0 - 2.5	1	3	1	3	2.7	2.3	19.0	12.1	.03	6.9
2.5 - 7.6	2	3	1	3	4.2	3.0	17.8	12.0	.05	5.7
7.6 - 15.2	2	3	1	2	4.5	3.5	17.8	11.7	.04	6.1

[1]Clay mineral type and amount determined by X-ray diffraction. A scale from 0 to 5 indicates relative amounts with 0 meaning none detected and 5 meaning that the type is dominant.

(fig. 1) (Heidmann 1974a). The chest was filled with small cylinders of soil and then placed in a chest-type freezer.

Numerous authors (Taber 1929, Haley 1953, Jumikis 1956, Higashi 1958, Kaplar 1971) described various types of freezing apparatus for conducting frost-heaving tests, most of which were elaborate and expensive. In addition, most of these experiments used cylinders of soil as large as 10 by 25 cm, which meant that not many samples could be studied at one time. The 3.3- by 7.6-cm cylinders used in this study are similar to the miniature cylinders described by Lambe (1956). The primary advantage of the smaller cylinders is that many more samples may be studied at one time.

A detailed description of the construction of the freezing chest and how the freezing tests were conducted is given by Heidmann (1974a). Only a brief description will be given here.

The freezing chest was designed to simulate an open system. Sifted oven-dried soil was placed in cylinders made of polyvinylchloride (PVC) plastic pipe covered on one end with cheesecloth. To simulate frost heaving as it occurs naturally, the soil samples should freeze from the surface downward. Therefore, the cylinders were insulated on the sides by imbedding them in a sheet of styrofoam. This sheet was then placed in a pan of water. The pan was set in a plywood box insulated on the sides and bottom with styrofoam insulation. The entire box was then placed in the freezer. Water in the pan was kept above the freezing point by means of a heating tape imbedded in the insulation underneath the pan.

Frost heaving at field bulk density.—Soil cylinders were filled with the weight of oven-dried soil (less than 2 mm) necessary to duplicate the field bulk density. It was necessary to wet the soil in order to pack all of the soil into the cylinders.

The cylinders with soil were placed in trays of tapwater and allowed to reach a constant weight, after which they were weighed to the nearest 0.1 g. The cylinders were then placed in the freezing chest. Each freezing experiment lasted for 10 days.

The surface of each sample was checked every 8 hours to determine onset of freezing. At the conclusion of the freezing period the amount of heaving (height of soil surface extending above) was recorded to the nearest millimeter. In addition, the total depth of freezing was measured for each cylinder.

The mean heave per day (table 3, Yobs.) for the various soil samples was analyzed by analysis of variance. Soil samples differed significantly ($P = 0.01$).

In general, the soil samples from BF, TP, and W-14 at the 2.5 to 7.6 and 7.6 to 15.2 cm depths heaved more than the other samples.

The soils at S-3 have been observed to heave spectacularly. Larson (1961) found that several hundred first-year ponderosa pine seedlings, over half of those in his study, heaved during one night in October 1957. Larson's study was located within the same enclosure from which the S-3 samples used in this study were collected. The heaving of these soil samples in the laboratory test was intermediate.
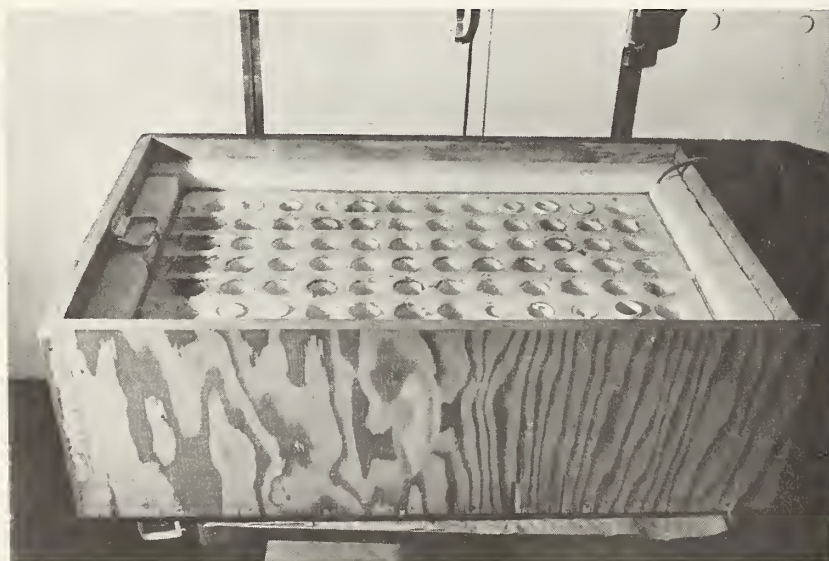

Figure 1.—Heaving characteristics of soils were studied in this plywood chest insulated with styrofoam.

Table 3.--Comparison of observed frost heaving and frost heaving as predicted by regression equation for six soils in Arizona

Location and soil depth (cm)	Yobs.	$\hat{Y}$	Yobs. $- \hat{Y}$
	- - - mm/day - - -		
Tie Park (TP)			
0 - 2.5	1.69	1.92	-.23
2.5 - 7.6	.86	1.42	-.56
7.6 - 15.2	3.04	2.14	+.90
Beaverhead Flat (BF)			
0 - 2.5	.48	1.64	-1.16
2.5 - 7.6	3.12	2.70	+.42
7.6 - 15.2	2.97	2.58	+.39
Fort Valley Experimental Forest-- S-3 West (S-3W)			
0 - 2.5	0.77	0.50	+.27
2.5 - 7.6	.91	.75	+.16
7.6 - 15.2	1.16	1.17	-.01
S-3 East (S-3E)			
0 - 2.5	1.28	1.25	+.03
2.5 - 7.6	1.27	1.09	+.18
7.6 - 15.2	1.05	1.62	-.57
Beaver Creek Watershed 14 (W-14)			
0 - 2.5	.86	1.04	-.18
2.5 - 7.6	1.74	1.95	-.21
7.6 - 15.2	2.29	2.19	+.10
Kelly Tank (Kelly)			
0 - 2.5	.30	-.19	+.49
2.5 - 7.6	.77	.81	-.04
7.6 - 15.2	1.42	1.50	-.08

$Y = -2.52 + 3.67 X_{BD} - .026 X_{SAND}$

Regression Analysis

All of the data collected for the various soil parameters were used in a series of stepwise regressions to develop an equation for predicting susceptibility to frost heaving.

The regression included all of the variables for all of the soils and depths. The highest simple correlation (r) of frost heaving was with bulk density (0.61), followed by montmorillonite (0.53). None of the other variables had a strong positive correlation with frost heaving. Potassium had a negative correlation of 0.44. Montmorillonite and bulk density showed an r = 0.67.

Bulk density was the variable entered in the first step of the regression. This variable accounted for 37 percent of the variation (R^2). When sand content was added in step two, 71 percent of the variation was accounted for. These two variables gave a regression equation of:

$$\hat{Y} = -2.52 + 3.67 X_{BD} - 0.026 X_{SAND}$$

where $\hat{Y}$ is heaving in millimeters per day.

By adding calcium, the multiple R^2 was increased to 83 percent, and the equation became:

$$\hat{Y} = -2.67 + 4.10 X_{BD} - .90 X_{CA} - .02 X_{SAND}$$

It is probably better to stop at step two, however, because it is easier to determine the bulk density and sand content for a particular soil than the calcium content.

The regression equation gives an index of frost heaving to be expected in laboratory tests. The $\hat{Y}$-variable is the expected heaving of a particular soil in millimeters per day when subjected to a constant ambient temperature of -3°C. A value less than 0.5 mm per day suggests heaving is not a problem. A value of 2 to 3 mm per day could indicate a serious heaving problem.

The regression performs reasonably well except for a negative value for Kelly at the 0 to 2.5 cm depth and an unusually large prediction for BF at the same depth (table 3).

DISCUSSION

The results of the various experiments in this study indicate that the susceptibility of forest soils to frost heaving may be predictable. The regression equation based on bulk density and sand variables requires further testing to determine its reliability. If the equation is reliable, then perhaps an index of heaving susceptibility can be derived similar to the one proposed by Haley (1953). In his system, a mean heaving of 0 to 0.5 mm per day is regarded as negligible, 2.0 to 4.0 mm is intermediate, and over 8 mm per day is high. None of the soils in the present study approached Haley's high rate, at least not in the laboratory. Soil at S-3 heaved almost 5 mm per night in December 1973, when the moisture content was approximately 50 percent. A laboratory heaving rate of 3 to 4 mm per day would seem to indicate a high susceptibility to frost heaving.

The two parameters used in the regression equation are bulk density and sand content. Reports indicate that a silty soil is most susceptible to frost heaving. Silt soils heave because the pores are small enough for a negative pressure to develop, but at the same time are large enough for water movement to occur (Penner 1958). Soils with high silt content thus tend to be ideally suited for segregation of soil water

and formation of ice lenses. A heavy clay soil has limited permeability because of small pores, even though the water is under tension. A sandy soil is permeable, but water is under little tension because of the larger pores.

When the six soils were compacted in another study, heaving increased as bulk density increased (Heidmann and Thorud 1975). It seems logical to assume that compacting the soil should reduce the rate of water flow. When the soil samples were placed in pans of water, it was noted that the water reached the surface of samples packed at the minimum bulk density in a matter of minutes. It took several hours, in most instances, for water to reach the surface of the most dense samples. The total equilibrium amount of water absorbed was essentially the same, however, for the three density levels. Since the least dense samples contained the same amount of water as the most dense there must be more unsaturated pores at the lower density.

Compacting the soil decreases the pore size and probably increases capillary flow. The soils studied do not contain a large percentage of clay but do have high silt contents. Because of their relatively low clay content, they probably cannot be compacted enough to restrict water flow. However, the high silt content suggests that compaction could lead to higher rates of water movement.

The size of the clay particles alone does not limit frost heaving. The type of clay mineral is also important. Exploratory tests conducted with montmorillonite and kaolinite revealed that montmorillonite did not heave during a 7-day freezing period, while kaolinite heaved as much as 200 percent (Heidmann 1974b). According to Grim (1952) the type of adsorbed ion determines to a large extent the thickness of water layers absorbed on the clay particles. Montmorillonite with sodium as the adsorbed ion is capable of holding large amounts of water between the particles. This water does not segregate. Montmorillonite with calcium, magnesium, or hydrogen as the adsorbed ion holds little water between clay particles. Frost heaving in this study was positively correlated with montmorillonite content, although this variable does not appear in the regression equation. The six soils studied generally contained greater amounts of both exchangeable calcium and magnesium than exchangeable sodium (table 2). The reason that montmorillonite is correlated with heaving of these soils is possibly because of higher amounts of adsorbed calcium and magnesium, which results in more water being available for segregation.

The other variables studied do not appear to be strongly correlated with frost heaving. This finding tends to substantiate the theory that frost heaving is directly related to the flow of water to the freezing front, and that soil texture and permeability—which affect the rate of flow—are of primary importance.

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